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Groundwater and Water Quality

Hydraulics, Water Resources and Coastal Engineering

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About the Editors

Ramakar Jha is a chair professor at the Department of Civil Engineering and has 30 years of experience in the field of Hydrology and water resources engineering. Dr Jha is presently working as Chair Professor in the Department of Civil Engineering, National Institute of Technology (NIT) Patna-INDIA, which is a Premier Institute in India under the Ministry of Human Resource Development, Government of India. Dr. Jha has served at various levels from Scientist-B to Scientist-E1 at National Institute of Hydrology (NIH), Roorkee, India and as Professor in the Department of Civil Engineering, NIT Rourkela. He has worked and working as Country Co-ordinator of UNESCO- GWADI and Principal Investigator for many International (EU-FP7, DAAD, ADB, AUS-Aid) and National research and consultancy projects (ISRO, DST, MoWR, MHRD). Moreover, he served as Chair for many administrative positions and received a coupel of international and national awards for research papers. Presently, he is working as Dr Rajendra Prasad Chair for Water resources under the Ministry of Water Resources, Government of India in the Department of Civil Engineering, NIT Patna, Bihar.

V. P. Singh A Texas A&M professor of Indian origin is receiving a prestigious award for his world-renowned work on water. Vijay P. Singh is receiving the 2013 Lifetime Achievement Award from the American Society of Civil Engineers-Environmental and Water Resources Institute, otherwise known as the ASCE-EWRI. The award is in recognition of Singh's work in the field of hydrology, which is the study of water in all aspects, such as quality, distribution, preservation, transportation, etc. Some of the work he has done has even created an entire new branch of hydrology – called entropic hydrology – that is connected to the study of entropy, which means essentially the study of order and disorder as it relates to the physical universe. His work is considered fundamental for flood planning and water modeling around the world. Since earning his doctorate degree, Singh has held teaching positions in some of the most well-known universities in the US. He was an Associate Research Professor of Civil Engineering at George Washington University from 1977-78, an Associate Professor of Civil Engineering at Mississippi University from 1978-81, and an adjunct professor as well as the coordinator of the Environmental and Water

Resources Systems Engineering Program at Louisiana State University from 1999-2006 and 2001-2006, respectively. Singh joined Texas A&M University in 2006, where he currently wears a number of different hats. He is a professor of biological and agricultural engineering, a professor of civil and environment engineering, and a Caroline and William N. Lehrer Distinguished Chair in Water Engineering (Hydrology). He has authored or edited around 10 published works in the fields of engineering and hydrology.

Chapter 1
Identification of the Parameters to Estimate the Capillary Rise from Shallow Groundwater Table Using Field Crop Experiments

Arunava Poddar, Navsal Kumar, and Vijay Shankar

Abstract Capillary rise from groundwater is known as the upward flow of moisture in the soil and is a significant component of soil water balance, specifically in the occurrence of a shallow groundwater table (SGT). Extraction of moisture from the SGT needs a proper understanding of the capillary rise. Various soil, crop, and environmental parameters possess a significant effect on the capillary rise. The objective of the study is to identify the impact of crop parameters on the capillary rise by performing field crop experiments on crops i.e., Wheat, Maize, Indian mustard, and Pea. Experiments are conducted using a Lysimetric setup on an agricultural farm at Hamirpur, Himachal Pradesh, India. Various models are considered to investigate the influencing parameters for capillary rise due to the crops for local climatic conditions. Regression analysis and performance indicators are used to perform analysis for the present study. Crop parameters (root depth, plant height, leaf area index), crop evapotranspiration, and soil moisture variation are found to affect capillary rise from the SGT. The proper understanding and estimation of capillary rise will supplement in optimized usage of moisture for irrigation purposes in areas with a SGT.

Keywords Capillary rise · Water table · Crop evapotranspiration · Plant transpiration · Soil moisture

1.1 Introduction

The irrigation system used effectively contributes to intelligent water use. Numerous aspects were developed which have altered the thinking regarding the irrigation systems management (Sharma and Kumar, 2021; Poddar et al. 2017; Kumar et al.

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2019b). Whenever water supplies are found to be limited, all available sources of moisture are assessed as potential sources of irrigation water.

Approximately 40% of world food requirement is fulfilled by irrigated agriculture and it is expected to keep playing an important role in fulfilling the expected world's demand for food (Poddar et al. 2021a). Nowadays, SGT can be considered as an alternative source for meeting crop-water requirements. Root water uptake (RWU) is a dynamic component of the water balance system required to manage the irrigation system efficiently (Kumar et al. 2019a, 2020). Various models for RWU have been evaluated to have optimized irrigation schedules for various crops (Ojha et al. 2009; Poddar et al. 2020, 2021b). The upward movement of water from the SGT is termed "capillary rise". Understanding and proper prediction of capillary rise can be an advantage for scheduling irrigation for different crops.

Numerous researchers have provided models to predict the capillary rise that occurs in the unsaturated zone (Prathapar et al. 1992; Zammouri 2001; Raes et al. 2003; Yang et al. 2011; Liu et al. 2014; Wang et al. 2016; Poddar et al. 2018). Since the parameters for each model varies, it is assumed that the parameters required to predict capillary rise are influenced by local conditions. Based on extensive literature review, it has been observed that capillary rise studies in hilly terrains are lacking. Hence, a study of the capillary rise occurring from SGT during RWU for the hilly region is required.

Hence, the present work aims to identify the parameters to predict capillary rise from the SGT.

1.2 Models Used for the Investigation

After an extensive literature review, six models are used for the comparative study. The models are Quasi-steady state analytical model (QSSAM) (Prathapar et al. 1992), Averianov formula (AF) (Schoeller 1961), Modified Transient state analytical model (MTSAM) (Jorenush and Sepaskhah 2003), Modified Averianov formula (MAF) (Yang et al. 2011), Quick capillary rise height estimation (QCRHE) (Liu et al. 2014) and groundwater uptake estimation method (GUEM) referred from (Wang et al. 2016). For details of the models, refer to the references given above.

1.3 Study Area

The site selected for study is an agricultural farm in Hamirpur, Himachal Pradesh, India which is situated in the mid-hills of the north-western Himalayas. The site is located at 31°42′40.824" N (latitude) and 76°31′33.384" E (longitude), and the elevation is 895 m (2,936 ft) above mean sea level. The average temperature of January (coldest) and June (hottest) is 8 °C and 34.3 °C respectively. Meteorological parameters were determined based on daily values of climatic variables obtained from All Weather Station (AWS) located at National Institute of Technology (NIT) Hamirpur.

1.4 Field Crop Experiments

A setup of two Lysimeters (1.5 × 1.5 × 2 m) was installed in the center of the experimental field at NIT, Hamirpur. Lysimeters were filled with sandy loam soil. Soil properties were examined experimentally in the Geotechnical Laboratory of Civil Engineering Department, NIT Hamirpur. Drainage from one of the Lysimeters is restricted to form water table conditions. A water table variation from 1.3–2.2 m is maintained with the help of piezometers. The other lysimeter is provided with free drainage. For the lysimeters, the daily soil moisture variation at an interval of 0.1 m is measured by the soil moisture profile probe (Diviner 2000 probe, M/S Sentek Sensor Technologies, Stepney, SA, Australia). The difference in moisture depletion between the two lysimeters represents the quantity of moisture contributed by the shallow GWT through the capillary rise. Table 1.1 shows the depth-wise mean textural fractions distribution (Trout et al. 1982), particle density, field capacity, permanent wilting point, and available water which were performed in a Geotechnical laboratory.

Field crop experiments were performed on wheat, maize, Indian mustard, and pea with details been given in Table 1.2. In Fig. 1.1, wheat, maize, peas, and Indian mustard can be seen in their crop development stage. Figure 1.2 shows the variation of crop parameters (root depth, plant height, and leaf area index (LAI)) observed at regular intervals during the crop period. Reference evapotranspiration (ET_0) is obtained using the FAO-56 Penman–Monteith equation.

1.5 Performance Evaluation Indicator for Models

The Coefficient of determination (R^2) (Luo and Marios, 2010) and Nash–Sutcliffe efficiency (NSE) (Legates and McCabe, 1999) are utilized to assess the execution of the models compared to observed values of capillary rise. R^2 indicates the degree of linear dependency and NSE validates the reliability of models and the maximum value for both evaluation indices is 1. The performance of a model is considered better when R^2 and NSE are higher and MBE is lower. The equations are

$$R^2 = \frac{\sum_{cr=1}^{n}\left(Ob_{cr} - \overline{Ob_{cr}}\right)\left(Es_{cr} - \overline{Es_{cr}}\right)}{\sqrt{\sum_{cr=1}^{n}\left(Ob_{cr} - \overline{Ob_{cr}}\right)^2}\sqrt{\sum_{cr=1}^{n}\left(Es_{cr} - \overline{Es_{cr}}\right)^2}} \tag{1.1}$$

$$NSE = 1 - \frac{\sum_{cr=1}^{n}\left(Ob_{cr} - Es_{cr}\right)^2}{\sum_{cr=1}^{n}\left(Ob_{cr} - \overline{Ob_{cr}}\right)^2} \tag{1.2}$$

Table 1.1 Soil properties for the study area

Soil depth (m)	Bulk density (g/c.c)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Particle density (g/c.c)	Field capacity (F_c) (cm^3/cm^3)	Permanent wilting point (PWP) (cm^3/cm^3)	Available water (cm^3/cm^3)
0.0–0.2	1.51	27.0	54.98	23.83	21.19	2.54	0.22	0.07	0.15
0.2–0.4	1.56	32.40	57.48	24.41	18.11	2.59	0.212	0.072	0.14
0.4–0.6	1.63	24.70	59.24	24.27	16.49	2.61	0.208	0.058	0.15
0.6–0.8	1.67	26.03	55.07	29.62	15.31	2.63	0.206	0.066	0.14
0.8–1.0	1.72	25.10	51.6	34.4	14.0	2.58	0.205	0.057	0.15

Table 1.2 Details of crops

Crop	Date of sowing	Date of harvesting	Duration (days)	Growth stages (days)				Irrigation provided (DAS)	Spacing (cm)
				I	II	III	IV		
Wheat (*Triticumaestivum*)	1st January 2015	4th May 2015	124	24	33	42	25	22nd, 39th, 50th, 71st, 90th, 118th	20 × 5
Maize (*Zea mays*)	11th May 2015	9th September 2015	120	22	36	40	22	20th, 44th, 64th, 89th	50 × 20
Pea (*Pisumsativum*)	18th September 2015	16th December 2015	90	18	30	25	17	10th, 22nd, 36th, 56th, 70th	40 × 15
Indian mustard (*Brassica Juncea*)	22nd January 2016	14th May 2016	114	19	32	38	25	11th, 25th, 37th, 59th, 91st	40 × 15

Fig. 1.1 Experimental view of wheat, maize, peas, and Indian mustard in the crop development stage

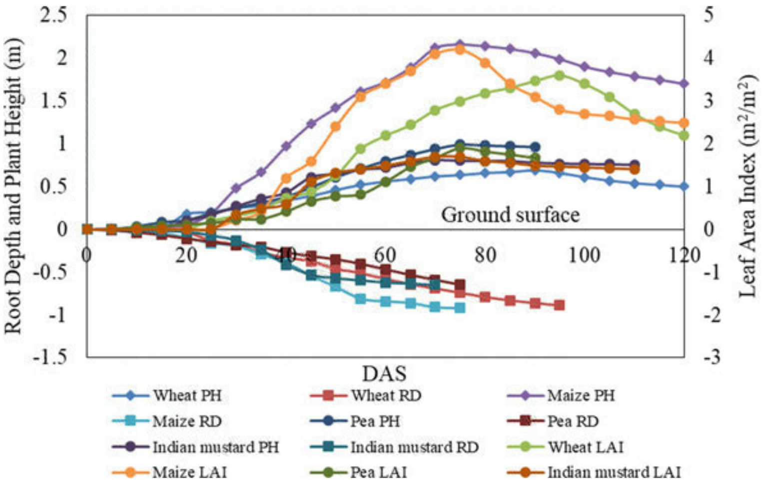

Fig. 1.2 Variation of root depth, plant height, and leaf area index for wheat, maize, and pea

where n = number of observations, Es_{cr} Ob_{cr}, = estimated and observed values. $\overline{Ob_{cr}}$ $\overline{Es_{cr}}$ = observed and estimated average values.

1.6 Results and Discussions

Performance evaluation of Models

Error statistics, i.e., R^2 and NSE values for the models are given in Table 1.3. R^2 and NSE values obtained from the models, i.e., QSSAM, AF, MTSAM, QCRH, and GUEM are lesser than 0.61 which indicates the poor performance of the models. Hence it is predicted that these models possess inadequate applicability for capillary rise estimation which is mostly due to inappropriate and tediously accessible input parameter requirement.

This necessitates the investigation of few easily accessible parameters which can be utilized to formulate a model to determine the capillary rise from the SGT.

Relation between the capillary rise and few easily accessible parameters

The SGT depth was fluctuated from 1.3 to 2.2 m to observe, variation of the capillary rise for wheat, maize, pea, and Indian mustard but brevity Fig. 1.3 shows the variation of capillary rise with days after sowing for wheat, maize, pea, and Indian mustard at 1.5 m depth. Figure 1.3 also shows the seasonal variations of each crop. It was observed that in the summer months, the values of the capillary rise were higher for the crops as compared to the winter months.

The relationship of capillary rise with root depth, plant height, LAI, ET_0, soil moisture, and groundwater table are investigated.

A linear relationship as specified by Table 1.4 ($p < 0.01$) exists between root depth, plant height, and LAI with high determination coefficients (r^2). These parameters are important in understanding plant growth, determining RWU, and irrigation scheduling (Stenitzer et al. 2007). Root depth, plant height, and LAI are easily

Table 1.3 Error statistics of estimated values in comparison with observed values

Crops	Evaluation indicators	Models					
		QSSAM	AF	MTSAM	MAF	QCRH	GUEM
Wheat	R^2	0.42	0.57	0.56	0.66	0.55	0.58
	NSE	0.48	0.55	0.58	0.71	0.59	0.52
Maize	R^2	0.52	0.54	0.59	0.68	0.51	0.58
	NSE	0.45	0.50	0.56	0.71	0.54	0.56
Peas	R^2	0.53	0.58	0.54	0.65	0.55	0.59
	NSE	0.46	0.54	0.59	0.69	0.59	0.54
Indian mustard	R^2	0.47	0.51	0.53	0.67	0.55	0.57
	NSE	0.49	0.53	0.55	0.73	0.58	0.59

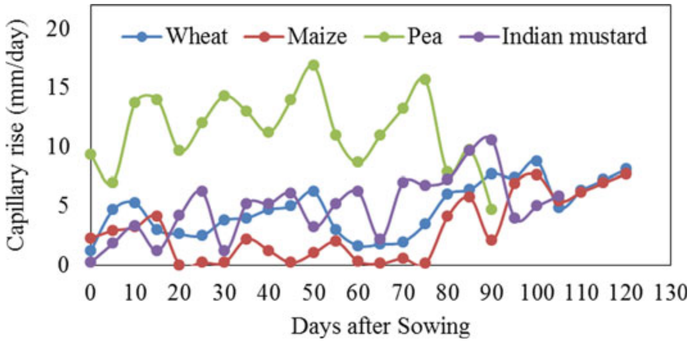

Fig. 1.3 Variation of the capillary rise for wheat, maize, pea, and Indian mustard at 1.5 m depth

accessible crop parameters and must be considered to predict capillary rise from the SGT.

The results of the experiments specify that a good correlation exists between the capillary rise and ET_0 at various depths of the water table. Determination coefficients between capillary rise and ET_0 at 1.3, 1.5, 1.7, 2.0 and 2.2 m SGT depths are 0.71, 0.77, 0.73, 0.68, and 0.61 respectively. Yang et al. (2011) also found capillary rise to have a considerable correlation with pan evaporation when the water table is at 1.5 m.

Table 1.5 shows an inverse correlation between capillary rise (at 1.3, 1.5, and 1.7 m depths) with soil moisture variation and available moisture in soil layers at 10–50 cm depths. Results from the study of Prathapar et al. (1992) were found consistent with the present study.

Table 1.4 Regression models of capillary rise with root depth, plant height, and leaf area index

Water table (m)	Root depth		Plant height		Leaf area index	
	Regression model	r^2	Regression model	r^2	Regression model	r^2
1.3	Y = 1.917x + 1.0237	0.63	Y = 2.017x + 1.0237	0.65	Y = 2.512x + 1.0237	0.64
1.5	Y = 3.634x + 1.352	0.74	Y = 3.371x + 1.352	0.76	Y = 3.987x + 1.352	0.77
1.7	Y = 8.543x + 1.354	0.67	Y = 9.026x + 1.686	0.67	Y = 9.926x + 1.121	0.67

Table 1.5 Regression model of capillary rise with root depth, plant height, and leaf area index

	Water level (m)	Soil moisture at various depths (cm)					
		0–20	20–40	40–60	60–80	80–100	100–120
Capillary rise	1.3	−0.487	−0.521	−0.549	−0.587	−0.545	−0.521
	1.5	−0.687	−0.723	−0.754	−0.766	−0.754	−0.742
	1.7	−0.552	−0.652	−0.642	−0.682	−0.647	−0.684

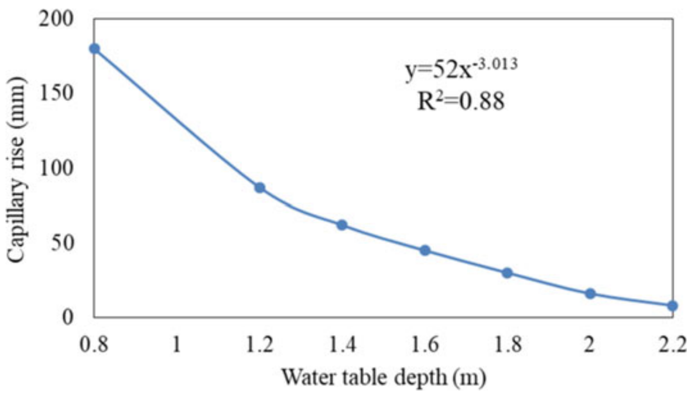

Fig. 1.4 Correlation between the capillary rise and water table depth

A power of exponential function with a high correlation coefficient was observed between the capillary rise and groundwater table depth as shown in Fig. 1.4 Similar results were found in the study of Warrick (1988) and Yang et al. (2011) which shows maximum capillary rise is directly proportional to water table depth.

From the above results and field crop experiments, it is found that root depth, plant height, LAI, ET_0, soil moisture, and groundwater table have good relationship with the capillary rise from SGT at depth 1.5 m. Hence an empirical relation can be formulated incorporating the above parameters.

1.7 Conclusion

The objective of the present study is to recognize and determine easily accessible parameters that affect the capillary rise in a cropped soil. Wheat, maize, pea, and Indian mustard were planted to examine the variation of capillary rise based on crops with fluctuation in the water table and to identify the major parameters that influence the capillary rise. It was observed that crop parameters (root depth, plant height, leaf area index), reference evapotranspiration, soil moisture, and groundwater table affected capillary rise. A linear relationship exists between the crop parameters (root depth, plant height, and leaf area index) with high determination coefficients. A close correlation exists between the capillary rise and reference evapotranspiration at various depths of the water table. Inverse correlation between capillary rise (at 1.3, 1.5, 1.7, 2.0, and 2.2 m depths) with soil moisture variation exists. As depth of the water table was increased, capillary rise obtained from the water table was observed to decrease. Hence root depth, plant height, leaf area index, reference evapotranspiration, soil moisture, and groundwater table can be used as variables to determine the capillary rise from the SGT in cropped soil. The work will further help in optimized irrigation scheduling for the regions having SGT.

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Chapter 2
Study of Groundwater Table Fluctuations in the Command Area of Bhagwanpur Distributary of the Eastern Gandak Project

Mani Bhushan, Souvik Mukherjee, Ashutosh Upadhyaya, and Lal Bahadur Roy

Abstract Study of groundwater fluctuation and estimation of groundwater recharge is an important aspect of water resource investigation, management, and development. In this paper, groundwater fluctuation has been analyzed and groundwater recharge has been estimated by water table fluctuation method as a case study for the data of the year from 1996 to 2003 for the command area of Bhagwanpur Distributary in Eastern Gandak Project in Bihar, India. Relation between rainfall and groundwater recharge has been estimated for the periods pre-monsoon to post-monsoon Kharif. During the observation period, groundwater level mostly remained within the top 6 m of subsurface soil at each of the three locations. Highest water table has been found at 0.27 m below the ground surface at Goraul-2 site in August 1999 during the monsoon period and the lowest water table of 6.35 m below ground surface was found at Bhagwanpur-1 location in 1996 during the month of May in pre-monsoon period. Average annual groundwater fluctuation for the period from May to May at Bhagwanpur-1, Saraiya-1, and Goraul-2 were +0.48 m, +0.0025 m and +0.18 m, respectively. The results of the yearly groundwater fluctuation indicate the rising trend of groundwater table. Average monsoon groundwater recharge at Bhagwanpur-1, Saraiya-1, and Goraul-2 during were 24.78%, 21.09%, and 30.27% of rainfall, respectively. Average monsoon rainfall during 1996–2003 was 1158.15 mm and average depth of groundwater recharge at Bhagwanpur-1, Saraiya-1, and Goraul-2 were 273 mm, 248 mm, and 334 mm. respectively.

Keywords Groundwater fluctuation · Groundwater recharge · Water Table Fluctuation Method (WTF)

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2.1 Introduction

Water sustains plants and plants sustain life, i.e., it has been rightly said that water is life. The primary source of water on the earth is precipitation. Most of the part of rainfall goes as runoff during monsoon season. Some quantity of water percolates the soil surface and joins the groundwater with a very slow rate of recharge. Study of groundwater level data is significant in evaluation, development, and management of groundwater (Nayak et al. 2003).

Groundwater recharge is defined as its entry into the saturated zone of water made available at the water table surface (Freeze and Cherry 1979). Accurate estimation of recharge is difficult because the process is complex and depends on numerous local factors, including precipitation amount, intensity and duration, evapotranspiration rate, runoff, geology, soil characteristics, topography, vegetation, and land use (Memon 1995).

Study of groundwater also provides information about crop growth. As all crops need good root aeration in order to produce optimum yield. Waterlogging of the entire root zone for a period of two or three days is likely to be fatal if it occurs at the crop germination stage but is not so serious during the active growing stage for irrigated dry crops (Smedema and Rycroft 1983).

According to USGS groundwater information, selected methods for estimating the groundwater recharge in humid regions are broadly classified into five types. These are water budget method, unsaturated zone method, groundwater method, stream flow method, and tracer method. For the present study, water table fluctuation (WTF) method which comes under Groundwater methods has been used for recharge calculation. As per Healy and Cook (2002), WTF method is applicable to unconfined aquifers and the aquifer in the study area is an unconfined aquifer.

2.2 The Study Area

Bihar is an eastern state in India. About 40% of the total cropped area in Bihar is flood affected. The temperature during summer is nearly 35–40 and 18–29 °C during winters. Heavy rainfall is witnessed during monsoon seasons. Sometimes little amount of rains is also observed during summers and winters. Also there is not much scope for improvement in the yield of crops due to waterlogging, poor drainage, and ill water management.

The command area of Bhagwanpur Distributary of the Eastern Gandak Project in Bihar lies in between 26° 01′ 21 ′N and 25° 52′ N and the longitude of 85° 09′ E to 85° 14′ E under the eastern Gandak Project, Bihar. Bhagwanpur distributary is a tail end distributary of the eastern Gandak Canal system. It is part of Vaishali Branch Canal which offtakes from Tirhut Main Canal. It has two sub-distributaries, i.e., Patehra sub-distributary and Rikhar sub-distributary. Bhagwanpur distributary starts near the village Manikpur, southeast to Saraiya and flows up to the villages Lalpura in Lalganj

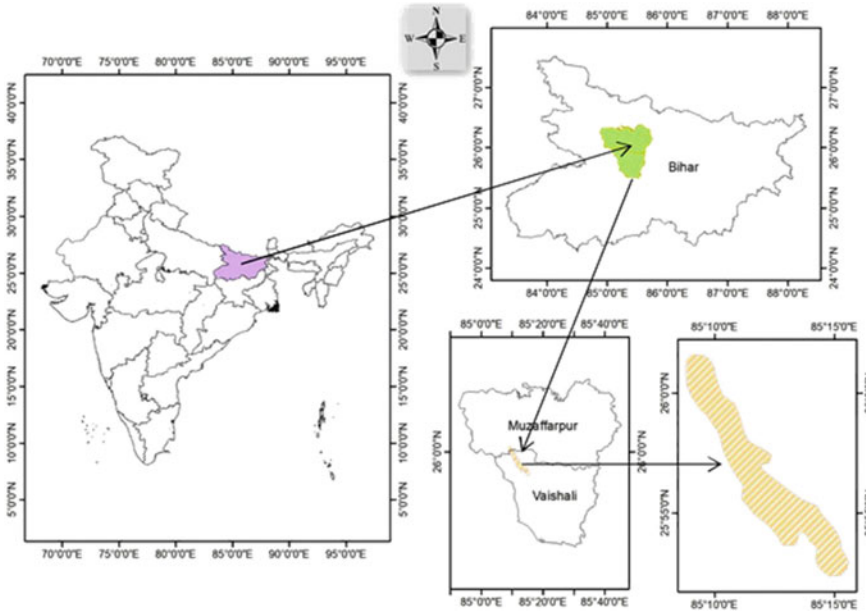

Fig. 2.1 Location map of the study area

block. Irrigation area covered by Bhagwanpur Distributary is almost around 4500 ha, which includes many villages in Saraiya block in Muzaffarpur district and Vaishali and Lalganj blocks in Vaishali district in the state of Bihar in India.

The study area lies under the agro-climatic zone I. Texture of the soil is mainly sandy loam and loam and the soil is young alluvial calcareous. Average slope of the land is varying between 0 and 10% and elevation is varying roughly between 50 and 60 m above from mean sea level. Average annual rainfall in the area is 1171.5 mm for the period 1981–2016. For the present study, three observation sites of Central Ground Water Board have been selected. These are Bhagwanpur-1 (Latitude 25.854 N, Longitude 85.320 E), Saraiya-1 (Latitude 26.016 N, Longitude 85.166 E), and Goraul-2 (Latitude 25.941 N, Longitude 85.325 E). All the three groundwater sites are very close to the study area. As there was no observation site available within the study area, analysis of data from these three sites have been done in the present study (Fig. 2.1).

2.3 Methodology

The groundwater levels are analyzed for the duration of 8 years between 1996 and 2003, for all the three observation sites. Data have been collected from Central Ground Water Board, India. Data are available for four different periods. These are

Table 2.1 Approximate percentage of deep percolation loss from rainfall (Source: USBR Drainage Manual 1993)

Texture of soil	Deep percolation (%)	Texture of soil	Deep percolation (%)
Loamy sand	30	Clay loam	10
Sandy loam	26	Silt clay loam	6
Loam	22	Sandy clay	6
Silt loam	18	Clay	6
Sandy clay loam	14		

Pre-Monsoon (observed between 20 and 30th May), Monsoon (observed between 20st and 30th August), Post-Monsoon Kharif (observed between 01 and 10th November), and Post-Monsoon Rabi (observed between 1st and 10th January). Trend of groundwater rise and range of groundwater fluctuation was determined by graphical approach.

The Water Table Fluctuation (WTF) Method is very simple and easy to apply as per Delin et al. (2007). Recharge by the WTF is estimated from the following equation by Healy and Cook (2002). To apply the WTF method Sy should be known or estimated and it is assumed that it remains constant over the time period of water table fluctuation.

$$R(tj) = Sy * \Delta H(tj) \tag{2.1}$$

where R(tj) is the recharge occurring in cm between time t0 and tj,

Sy is specific yield (dimensionless) and

ΔH (tj) is the water table rise in cm attributed to the recharge period.

Main challenge of WTF method is to estimate the value of specific yield. From the "Report of the Groundwater Resource Estimation Committee" by the Ministry of Water Resources Govt. of India (2009), it has been noted that for sandy alluvial soil in India, specific yield value varies between 12 and 18%. Therefore for this study, specific yield value has been assumed to be 15%, i.e., average of the two values as given in Table 2.2.

For the estimation of groundwater rise or build up during pre-monsoon to post-monsoon Kharif, deep percolation from rainfall is very important. Therefore, based on deep percolation loss as given in Table 2.1 and specific value as given in Table 2.2, groundwater rise can be estimated.

2.4 Results and Discussion

It is observed from Figs. 2.2, 2.3, and 2.4, which during each year for the period between 1996 and 2003, groundwater level in post-monsoon Kharif was always

Table 2.2 Specific yield for different kind of geological formation in the zone of water table fluctuation (*Source* Ministry of Water Resource, Government of India, 2009)

Soil formation	Range of specific yield in percentage
Sandy alluvial area	12–18
Valley fills	10–14
Silty/clayey alluvial area	5–12
Granites	2–4
Basalts	1–3
Laterite	2–4
Weathered phyllites, shales, schist and associated rocks	1–3
Sandstone	1–8
Limestone	3
Highly karstified limestone	7

higher than that of pre-monsoon. It indicates that significant amount of recharge takes place every year during monsoon.

Groundwater zoning is done from waterlogging point of view. Higher the groundwater level, more likely that affects the optimum growth of crops because subsurface waterlogging within the root zone creates the aeration problem. Groundwater level below 3 m does not affect the crop growth. Therefore, it is a safe zone for crops. Most of the crops have root zone less than 2 m. Therefore below this depth, groundwater zone varies from worst to bad. Beyond 2 m of depth alarming zone starts. Based on this concept groundwater zoning has been done and shown in Table 2.3.

It is observed from Fig. 2.2 that during Monsoon in 2004, the groundwater table reached within the top 1 m soil depth. For crops with root zone depth within top 1 m or less than 1 m, this depth of water table is not desirable. Even in the post-monsoon

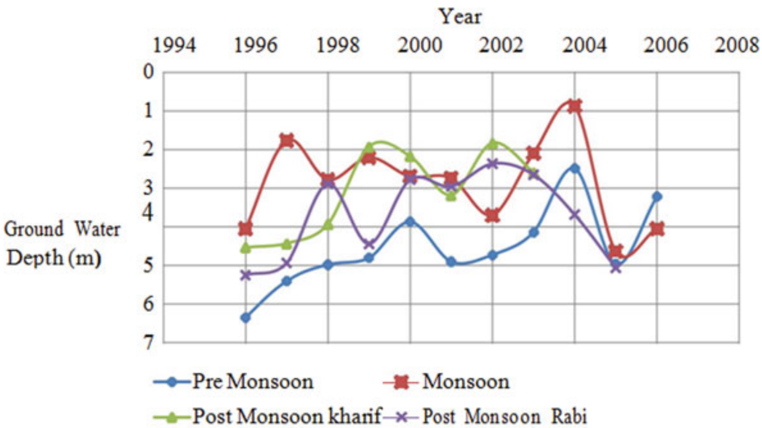

Fig. 2.2 Fluctuation of groundwater table at Bhagwanpur-1

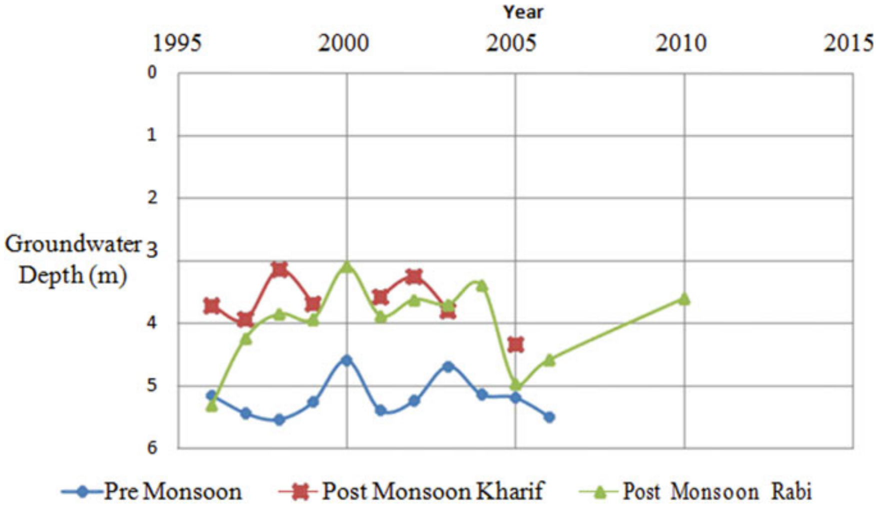

Fig. 2.3 Fluctuation of groundwater table at Saraiya-1

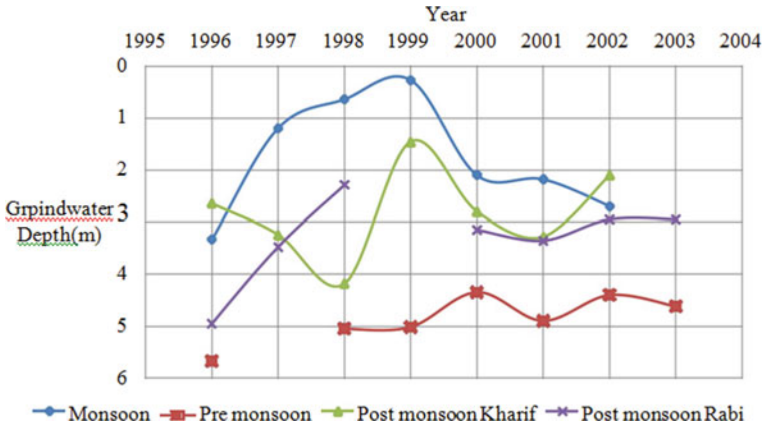

Fig. 2.4 Fluctuation of groundwater table at Goraul-2

season in 1999 and 2002 the water table is within 2 m from soil surface. Therefore, the crops with high root zone depth may suffer from subsurface waterlogging.

For the year from 1997 to 1999, there is a tendency of rising water table during monsoon season as shown in Fig. 2.4. Particularly in the year 1999, the groundwater table during monsoon and post-monsoon Kharif varied within 1.5 m, which will be harmful for most of the cereal crops. The monsoon groundwater table depths in 1998 and 1999 are 0.64 m and 0.27 m respectively, which are deeply encroach the root zone depth causing high damage to crops during this period. At Goraul-2 the pre-monsoon groundwater table remains well below ground level varying between 4 to

Table 2.3 Groundwater depth at Bhagwanpur-1 in Vaishali district during 1996–2006

Year of observation	Pre-monsoon (m)	Monsoon (m)	Post-monsoon Kharif (m)	Post-monsoon Rabi (m)	Maximum fluctuation (m)	Remarks
1996	6.35	4.05	4.53	5.25	2.3	Safe
1997	5.4	1.77	4.43	4.93	3.63	Bad
1998	4.98	2.78	3.93	2.89	2.2	Alarming
1999	4.8	2.21	1.93	4.44	2.87	Bad
2000	3.87	2.7	2.17	2.78	1.7	Alarming
2001	4.9	2.74	3.18	2.96	2.16	Alarming
2002	4.73	3.7	1.83	2.37	2.9	Bad
2003	4.14	2.1	2.6	2.65	2.04	Alarming
2004	2.49	0.88	NA	3.68	2.8	Worst
2005	4.96	4.63	NA	5.06	0.43	Safe
2006	3.22	4.05	NA	NA	NA	Incorrect

6 m. But, in the monsoon it remains within top 3 m and in post-monsoon Kharif, the groundwater table remains between 1 and 4 m of soil depth, which indicates that the recharge rate at Goraul-2 is higher than that at Bhagwanpur-1 and Saraiya-1 stations.

For the site Saraiya-1, as shown in Fig. 2.3 and Table 2.4, data for monsoon period were unavailable. The reason behind unavailability of data is that due to flood during monsoon the observation well could be submerged. But, observing the data of the other sites, it can be interpreted that groundwater table during monsoon may vary between 2 and 3 m or even higher during the observation period.

Table 2.4 Groundwater depth at Saraiya-1 in Muzaffarpur District from 1996 to 2006

Year of observation	Pre-monsoon (m)	Post-monsoon Kharif (m)	Post-monsoon Rabi (m)	Maximum fluctuation (m)	Remarks
1996	5.16	3.72	5.31	1.44	Safe
1997	5.44	3.94	4.24	1.5	Safe
1998	5.54	3.14	3.85	2.4	Safe
1999	5.26	3.69	3.93	1.57	Safe
2000	4.59	NA	3.09	1.5	Safe
2001	5.39	3.58	3.88	1.81	Safe
2002	5.24	3.26	3.62	1.98	Safe
2003	4.69	3.8	3.7	0.99	Safe
2004	5.14	NA	3.39	1.75	Safe
2005	5.19	4.34	4.96	0.85	Safe
2006	5.5	NA	4.58	0.92	Safe

From Tables 2.6, 2.7, and 2.8, it is observed that the average groundwater fluctuation between pre-monsoon and post-monsoon rabi is the highest at Goraul-2, i.e., 1.63 m and the lowest at Saraiya-1, i.e., 1.21 m. At Bhagwanpur-1, average groundwater fluctuation between the same period for a year is 1.36 m. On yearly basis comparison between May and May, at Saraiya-1 groundwater level remained almost constant with an average rise of 0.0025 m per year. But Bhagwanpur-1 site shows a tendency of rising water table with an rate of 0.48 m per year, whereas for Goraul-2 average groundwater rise is moderate, i.e., 0.18 m per year. During post-monsoon rabi, Goraul-2 shows a high rise at an average of 1.03 m per year. At the other two sites, the increments are 0.37 m and 0.23 m per year respectively. At Bhagwanpur-1 average pre-monsoon groundwater rise, i.e., 0.48 m is higher than the average post-monsoon rabi groundwater rise, i.e., 0.37 m. At Goraul-2 and Saraiya-1, the average groundwater rise between post-monsoon rabi is higher than that of pre-monsoon. Observing all the fluctuation data, it is clearly seen that at all the three locations groundwater level is rising (Table 2.5).

Table 2.5 Groundwater depth at Goraul-2 in Vaishali District from 1996 to 2003

Year of observation	Pre-monsoon (m)	Monsoon (m)	Post-monsoon Kharif (m)	Post-monsoon Rabi (m)	Maximum fluctuation (m)	Remarks
1996	5.67	3.33	2.64	4.95	3.03	Alarming
1997	NA	1.2	3.24	3.48	NA	Bad
1998	5.5	0.64	4.18	2.29	4.86	Worst
1999	5.02	0.27	1.46	NA	NA	Worst
2000	4.35	2.1	2.8	3.15	2.25	Alarming
2001	4.9	2.18	3.28	3.36	2.72	Alarming
2002	4.4	2.7	2.1	2.95	2.3	Alarming
2003	4.62	NA	NA	2.95	NA	Alarming

Table 2.6 Comparison of groundwater fluctuation during different periods at Bhagwanpur-1

Season	Fluctuation (May–Jan) (m)	Fluctuation (May–May) (m)	Fluctuation (Jan–Jan) (m)
1996–97	+1.1	+0.95	–
1997–98	+0.47	+0.42	+0.32
1998–99	+2.09	+0.18	+2.04
1999–2000	+0.36	+0.93	−1.55
2000–2001	+1.09	−1.03	+1.66
2001–2002	+1.94	+0.17	−0.18
2002–2003	+2.36	+0.59	+0.59
2003–2004	+1.49	+1.65	−0.28
Average	+1.36	+0.48	+0.37